ν-Nucleus Scattering Yields: Interplay of Neutrino Flux, Cross sections and Nuclear Effects

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MINERνA Collaboration Meeting – February 2013

ν – H / D Scattering

Life was simpler when our targets were nucleons as opposed to nuclei.

$$\sigma = \frac{N_{obs} - N_{bgd}}{\Phi * N_{targets} * \varepsilon}$$

Number of neutrinos (flux)

Reconstruction efficiency

Number of nuclei

Neutrino Nucleus Scattering

What do we observe in our detectors?

- The events we observe in our detectors are convolutions of:
  $Y_{c\text{-like}}(E) \; \alpha \;\; \phi(E' \geq E) \otimes \sigma_{c,d,e..}(E' \geq E) \otimes Nuc_{c,d,e..\rightarrow c}(E' \geq E)$

- $\mathbf{Y_{c\text{-like}}(E)}$ is the event energy and channel / topology of the event observed in the detector. It is called c-like since it appears to be channel c but may not have been channel c at interaction.

- That is the topology measured in the detector is what we observe in the detector and not necessarily what was produced at the initial interaction.

- The energy E is not given by knowing the E of the incoming particle as in charged particle scattering, but is the sum of energies coming out of the nucleus and measured in the detector.

Neutrino Nucleus Scattering

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- $\phi(E)$ is the energy dependent neutrino flux that enters the detector.

- We can, with considerable effort, estimate the incoming neutrino energy distribution to ≤ 10% absolute and **≤ 7% energy-bin to energy-bin accuracy** with sophisticated Monte Carlos that depend on knowledge of the hadron production spectra off the target and careful modeling of the subsequent beam components.

Neutrino Nucleus Scattering

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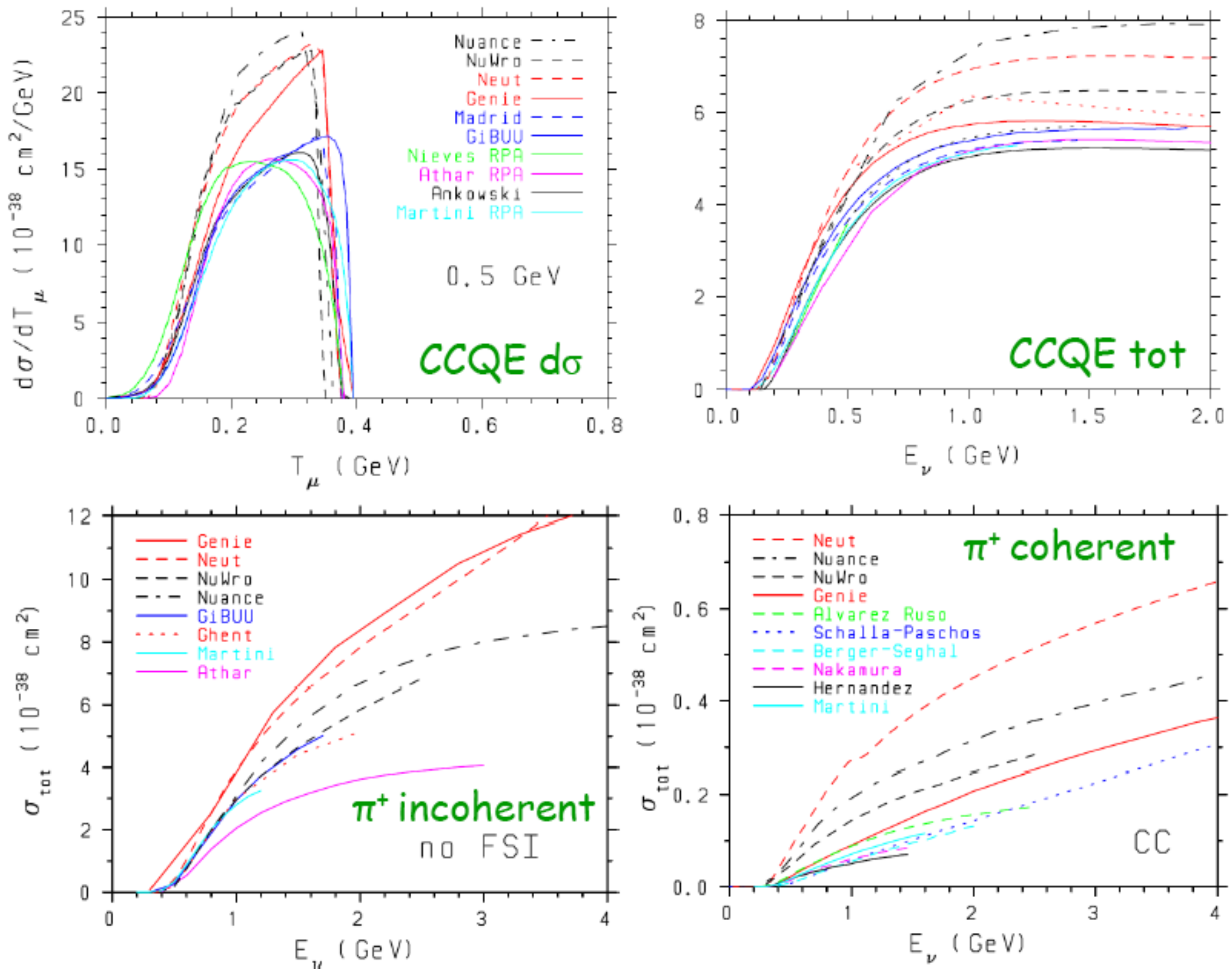
- $\sigma_{c,d,e..}(E' \geq E)$ is the measured or the Monte Carlo (model) energy dependent neutrino cross section off a **nucleon within a nucleus.**
- Form factors are modified within a nucleus compared to a nucleon.
  - Analogous to the difference between PDFs and nuclear NPDFs
- The width of the Δ changes within a nucleus.
- A bit tricky to measure without the next convoluted quantity….

Range of Existing Model (MC) Predictions off C

NuInt09 – Steve Dytman



Neutrino Nucleus Scattering

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- **$Nuc_{c,d,e..\rightarrow c}(E' \geq E)$ – Nuclear Effects**
  - In contemporary neutrino experiments the interactions do not occur on a free nucleon but rather nucleon(s) within a nucleus and there are many nuclear effects that have to be considered.
  - In general the interaction of a neutrino with energy E' creating initial channel d,e… can appear in our detector as energy E and channel c
  - **Nuclear Effects** – a migration matrix that mixes produced/ observed channels and energy.

What are these Nuclear Effects **$Nuc_{c,d,e..\rightarrow c}$ (E'≥ E)** in Neutrino Nucleus Interactions?

- Target nucleon in motion – classical Fermi gas model or the superior spectral functions (Benhar et al.)
- Certain reactions prohibited - Pauli suppression
- Meson exchange currents: multi-nucleon initial states
- Form factors and resonance widths are modified within the nuclear environment. (Butkevich / Kulagin, Tsushima et al.)
- Produced topologies are modified by final-state interactions modifying topologies and possibly reducing **detected** energy.
  - Convolution of $\delta\sigma(n\pi)$ x formation zone uncertainties x π-charge-exchange/ absorption (nuclear density uncertainties)
- Cross sections and structure functions are modified and parton distribution functions within a nucleus are different than in an isolated nucleon. Important for DIS AND Transition region events!

What do we observe in our detectors?

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  $Y_{c\text{-like}}(E) \propto \phi(E' \geq E) \otimes \sigma_{c,d,e..}(E' \geq E) \otimes Nuc_{c,d,e..\rightarrow c}(E' \geq E)$

  effective $\sigma_c^A(E)$

- Experimentally, the last two terms convoluting the initial nucleon (within a nucleus) cross section and nuclear effects are combined into an effective cross section $\sigma_c^A(E)$ and we now have:

$$\sigma_{c\text{-like}}^A(E) \propto Y_{c\text{-like}}^A(E, Nuc(E' \geq E)) / \phi(E' \geq E)$$

- Note that the **effective cross section $\sigma_c^A(E)$ measured depends on the incoming neutrino energy spectrum and the involved nuclear effects that populate the yield $Y_c^A(E)$.**

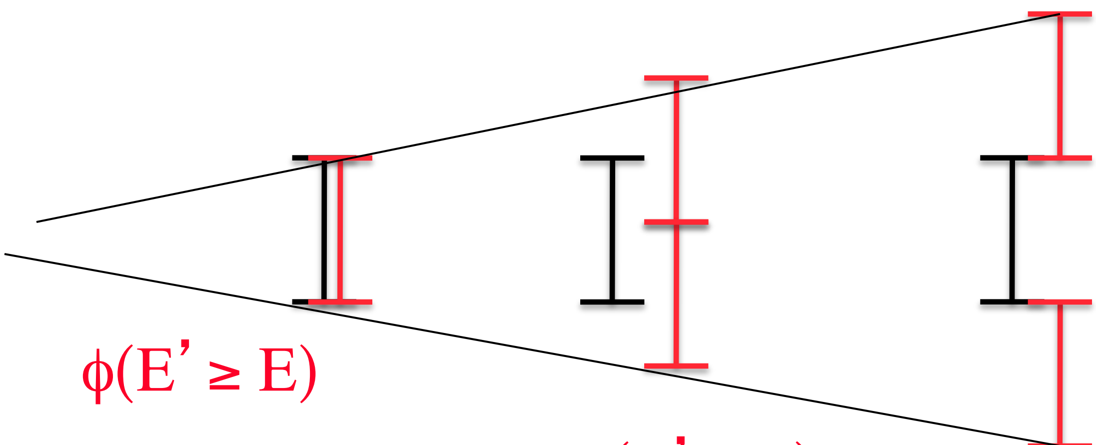
- This implies that, for example, the effective $\sigma_{\pi 0}^C$ (1 GeV) measured in the MiniBooNE Booster beam **will be different** than the same effective $\sigma_{\pi 0}^C$ (1 GeV) observed by MINERvA in the higher energy NuMI beam due to, for example, more feed down from multi-pi events via pion absorption in the NuMI beam.

Systematics

Flux for $E > E^{thresh}_{\Delta}$ up 1 s.d.

Cross section for Δ production up 1 s.d.

Probability for π absorption up 1 s.d.



Quasi-elastic candidates increase.

$\phi(E' \geq E)$

$\sigma_{c,d,e..}(E' \geq E)$

$Nuc_{c,d,e..\to c}\,(E' \geq E)$

Significant Implications for Oscillation Experiments

- Can not simply plug in effective $\sigma_{\pi 0}^{A}$ from experiments in a significantly different beam.
- In a two-detector oscillation experiment the neutrino flux entering the far detector is altered from the neutrino flux at the near detector due to oscillations.
- The σ_{c}^{A} (E) effective that should be applied to expectations (Monte Carlo) at the far detector is NOT the same as that which we would measure at the near detector. **However, the near detector results give us an excellent starting point for calculating the difference.**
- **The convoluted $\phi(E' \geq E)$ X $\sigma(E)$ X Nuc(E'≥ E) systematics need to be correctly incorporated in determining the systematics of oscillation parameter measurements.**

What can we do to study this?

- Lots of CPU to model the effect….
- Study same "-like" channels in the LE and ME beam
- Reweight the LE near detector beam spectra to the MINOS far detector measured oscillated spectra. What do we see for "QuasiElastic – like " events.
- ……….

Summary and Conclusions

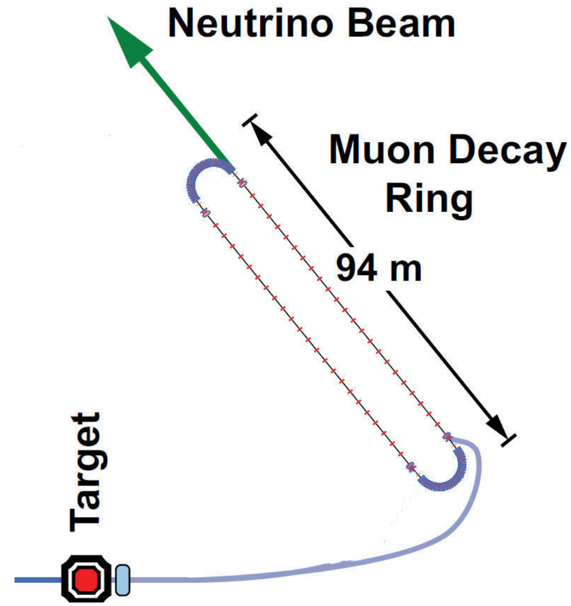
- Nuclear effects, present in the data of all contemporary neutrino oscillation experiments, mixes channels and changes energy between produced and final states (observed).
- Observed results for a specific channel from one detector does not transfer to another detector unless they are using the same neutrino beam. **What is a "standard candle"?**
- Need to study these effects on a variety of nuclear targets and with a variety of incoming neutrino energy distributions. **MINERvA in the LE and ME beams!**
- To untangle these effects, a significant step forward would be a high-statistics neutrino-hydrogen /deuterium experiment.
- Best would be in a neutrino beam with a flux that we know to $\approx 1\%$.

Backup

Can we Actually MEASURE these Differences in the 0.5 – 4 GeV region

νSTORM Neutrinos from Stored Muons

- High-Precision ν interaction physics program.
  - The νSTORM beam will provide a very well-known ($\delta\ \phi(E) \approx 1\%$) beam of ν and $\overline{\nu}$.
    - ν_e and $\overline{\nu}_e$ cross-section measurements.
    - ν_μ and $\overline{\nu}_\mu$ cross-section measurements

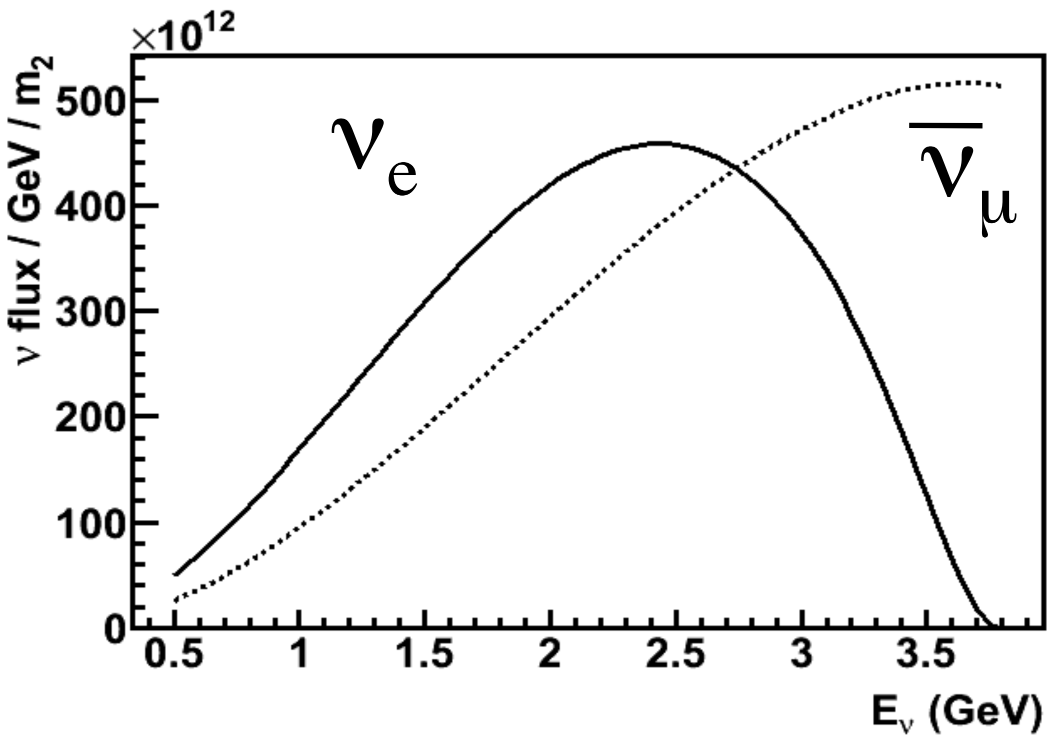


- Address the large Δm^2 oscillation regime, make major contribution to the study of sterile neutri
  - Either allow for precision study (in many channels), if they exist in this regime.
  - Or greatly expand the dis-allowed region.
- Provide a μ decay ring test demonstration and μ beam diagnostics test bed.
- Provide a precisely understood ν beam for detector studies.
- **Change the conception of the neutrino factory.**

The νSTORM Neutrino Beam

$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$ $\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$

- A high-intensity source of ν_e events for experiments.



3.8 GeV μ^+ stored, 150m straight, flux at 100m

(thanks to Sam Zeller and Chris Tunnell!)

μ^+

Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421

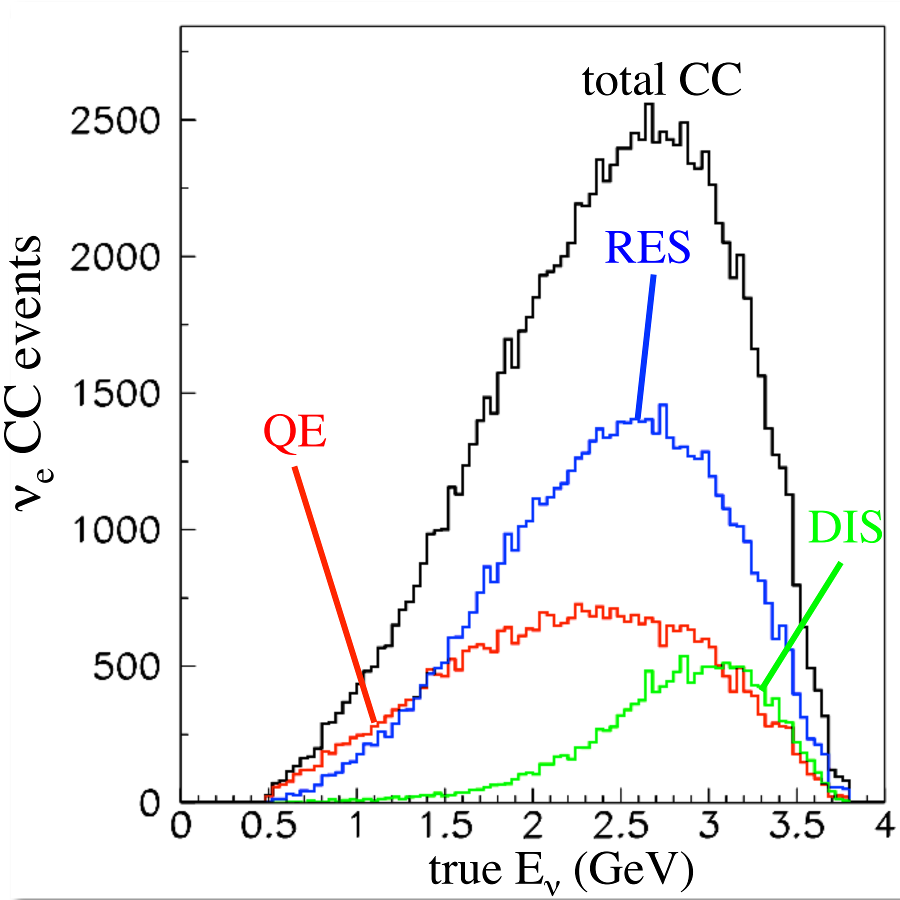
μ^-

Channel	N_{evts}
$\bar{\nu}_e$ NC	709,576
ν_μ NC	1,584,003
$\bar{\nu}_e$ CC	1,784,099
ν_μ CC	4,626,480

event rates per 1E21 POT - 100 tons at 50m

ν_e Event Fractions in νSTORM

- ν_e produced by 3.8 GeV μ^+ beam.



out of the CC modes:

* 56% resonant

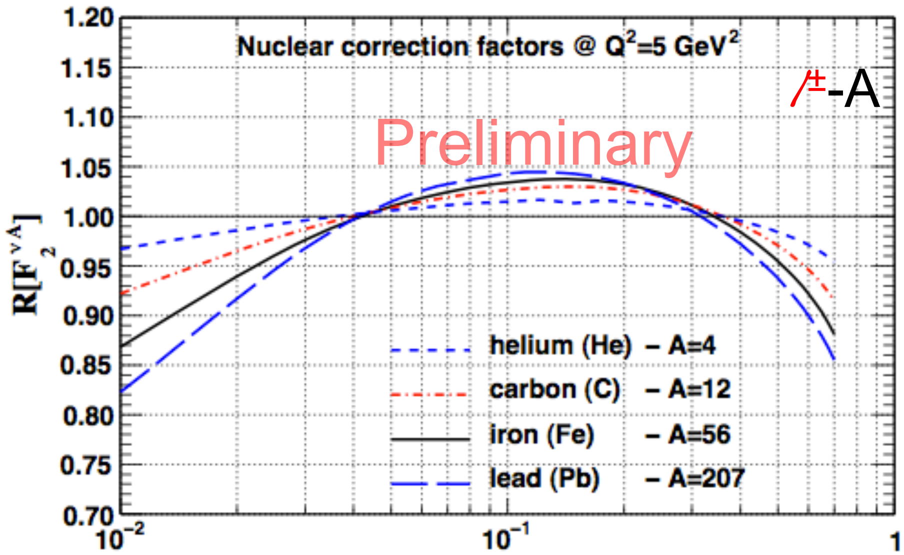
* 32% QE

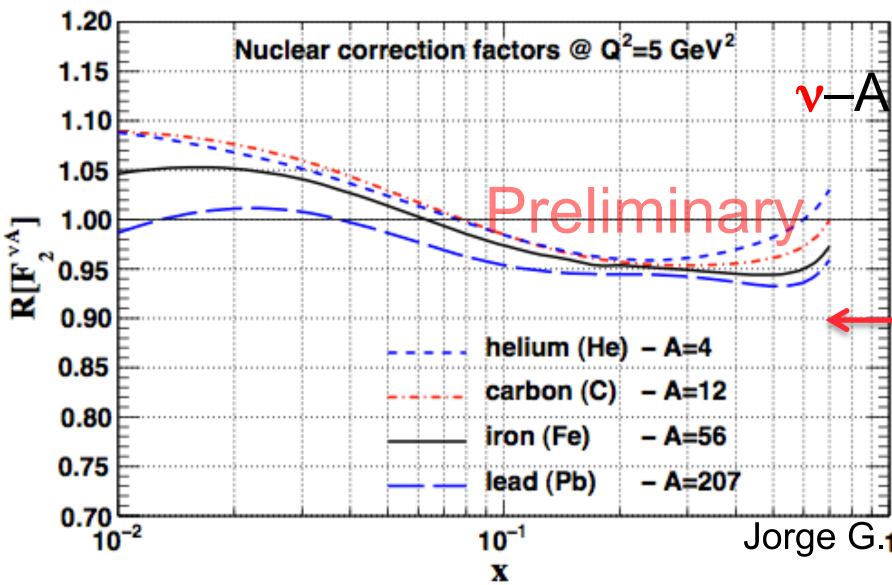
* 12% DIS

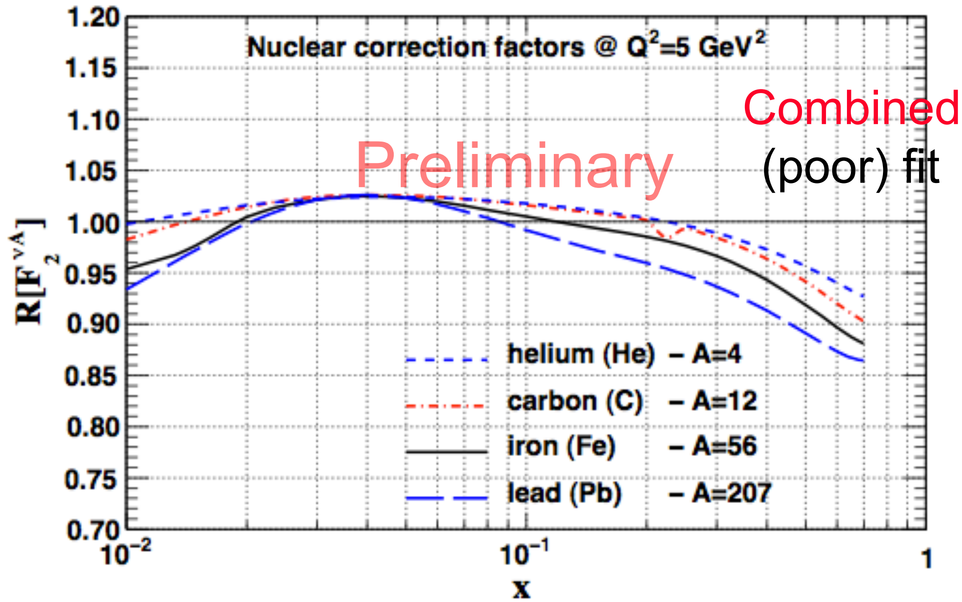
- For $\overline{\nu}_e$ sample, 52% resonant, 40% QE, 8% DIS)

What could MINERνA Contribute?

Preliminary Predictions for MINERνA Targets





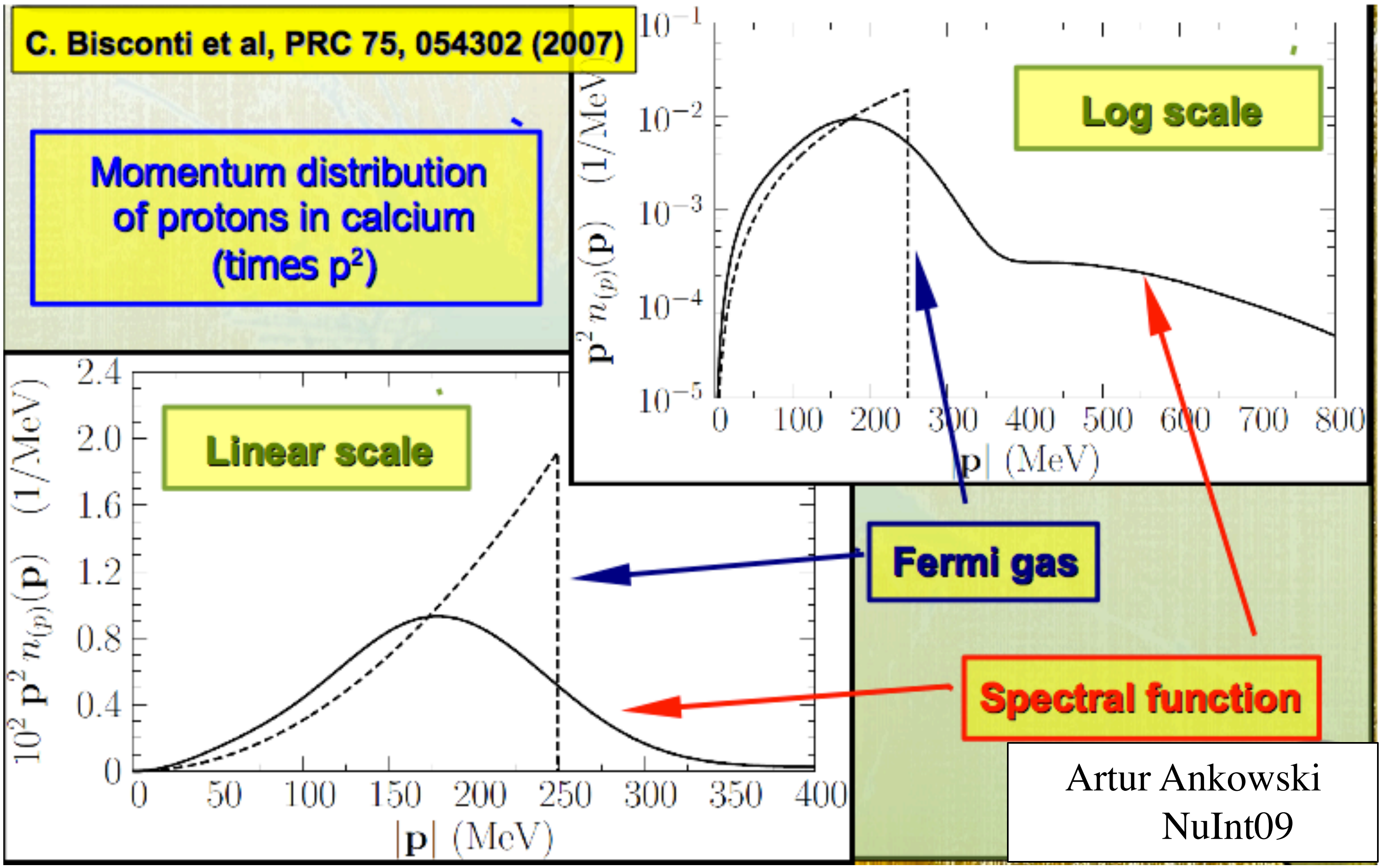


Careful! Based on analysis of NuTeV ν-Fe results and scaled in A **as charged lepton nucleus** scattering results!

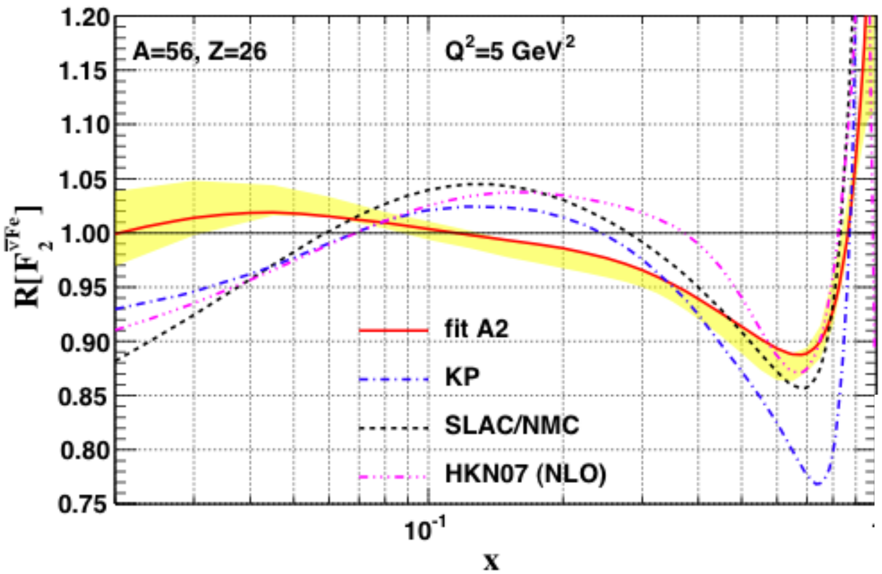
(Karol Kovarik – Katlsruhe)

Fermi Gas vs. Spectral Function p Distribution

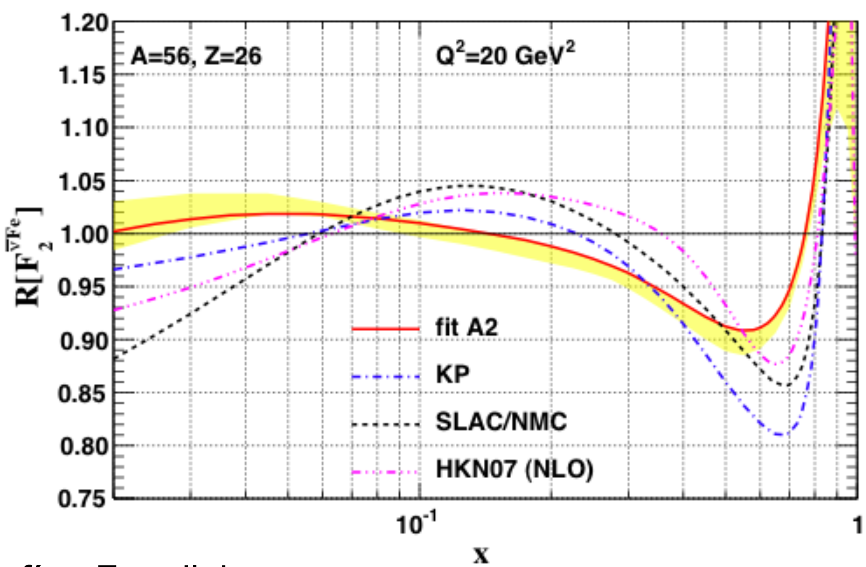
Bodek – Ritchie adds high p tail to FG due to SRC



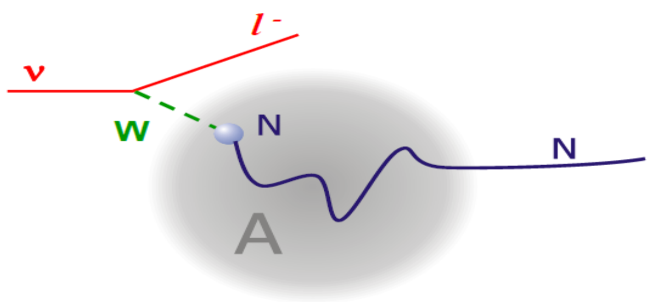
F_2 Structure Function Ratios: $\bar{\nu}$-Iron

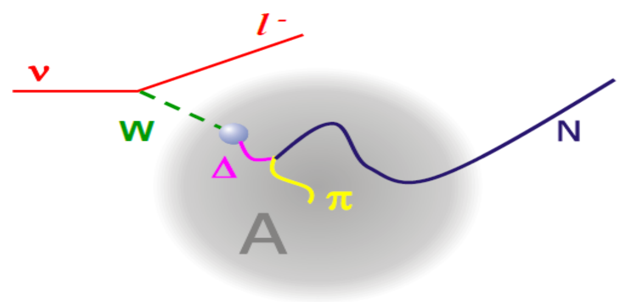


$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$



Final State Interactions can mimic a QE event

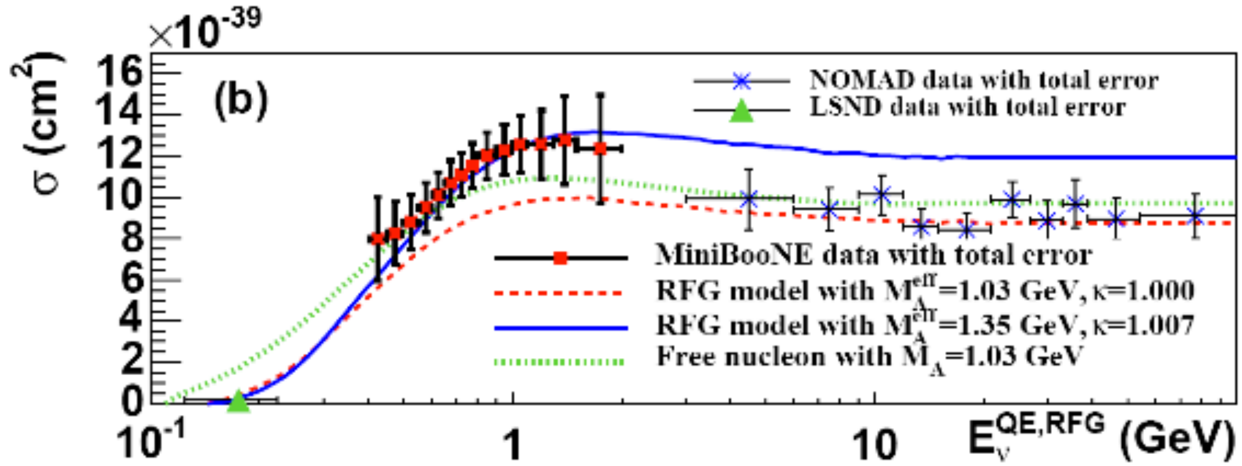


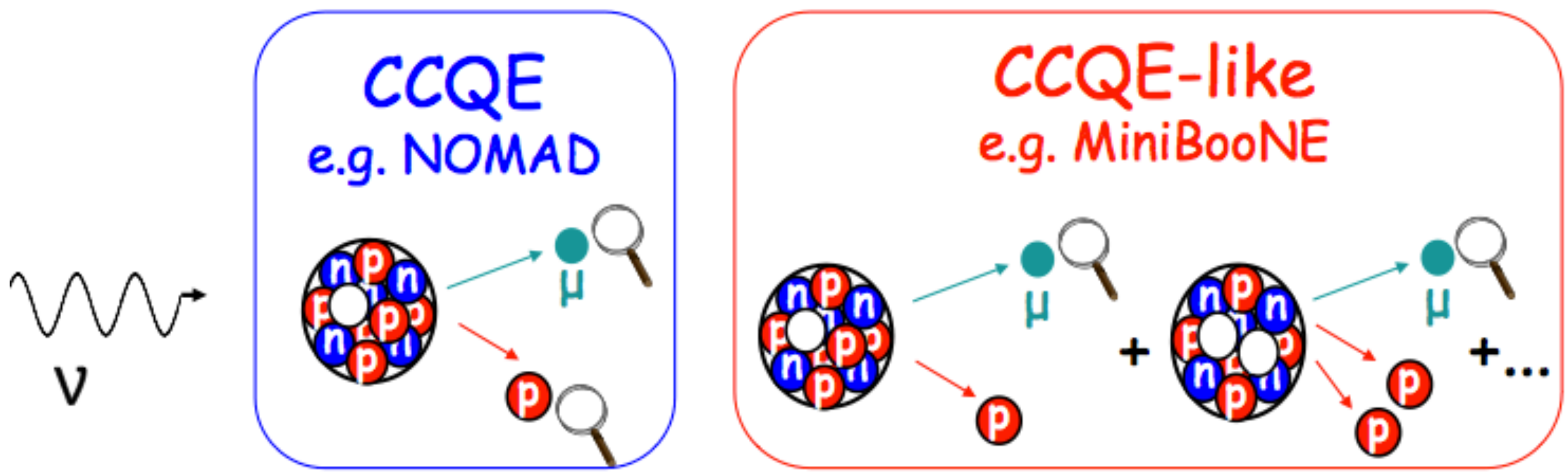


- Define a class of events as **"QE-like"** that have the apparent topology but can have been produced as something other than QE.

QE and QE-like events

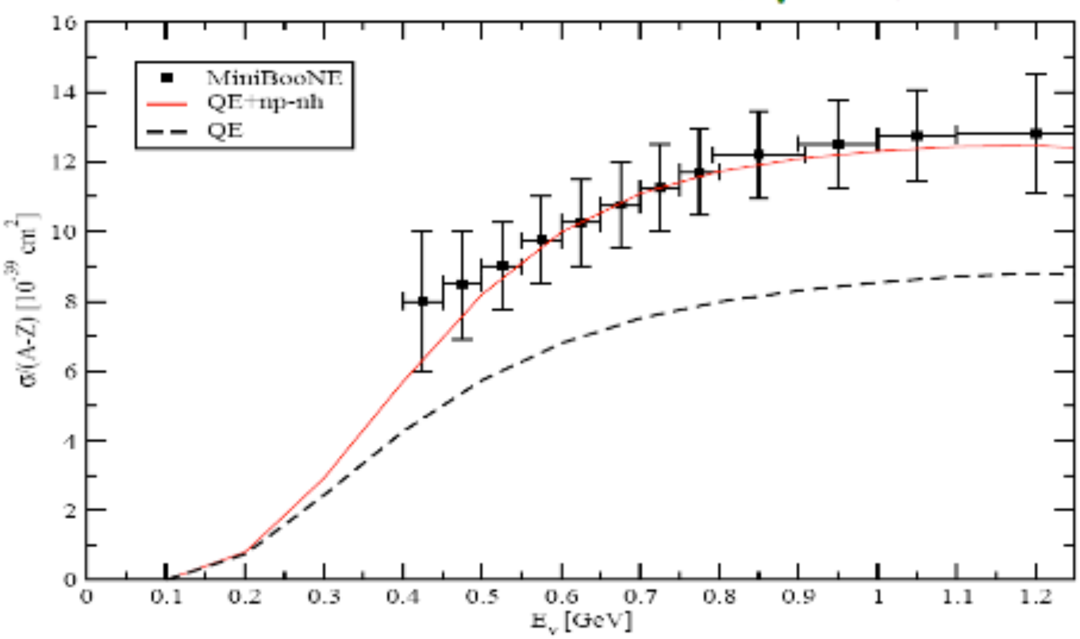
M.Martini
NuFact09

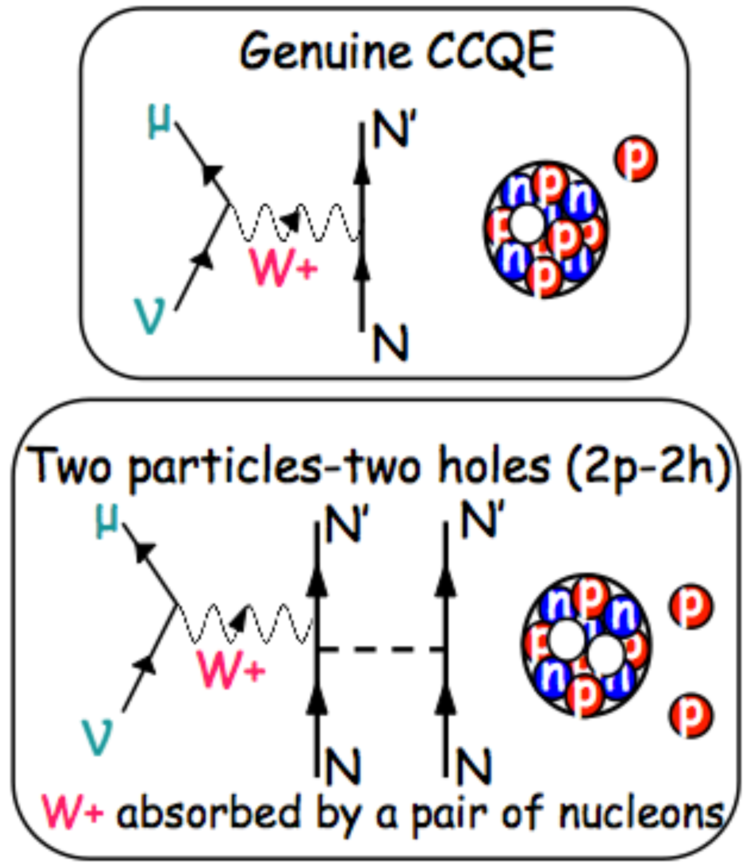




Meson Exchange Currents – 2p2h Effects
CCQE and CCQE-like

Inclusion of the multinucleon emission channel (np-nh)

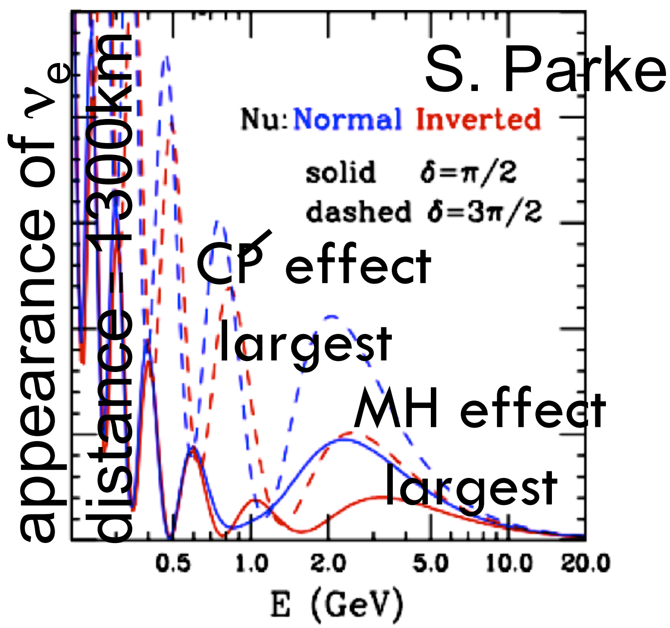




M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

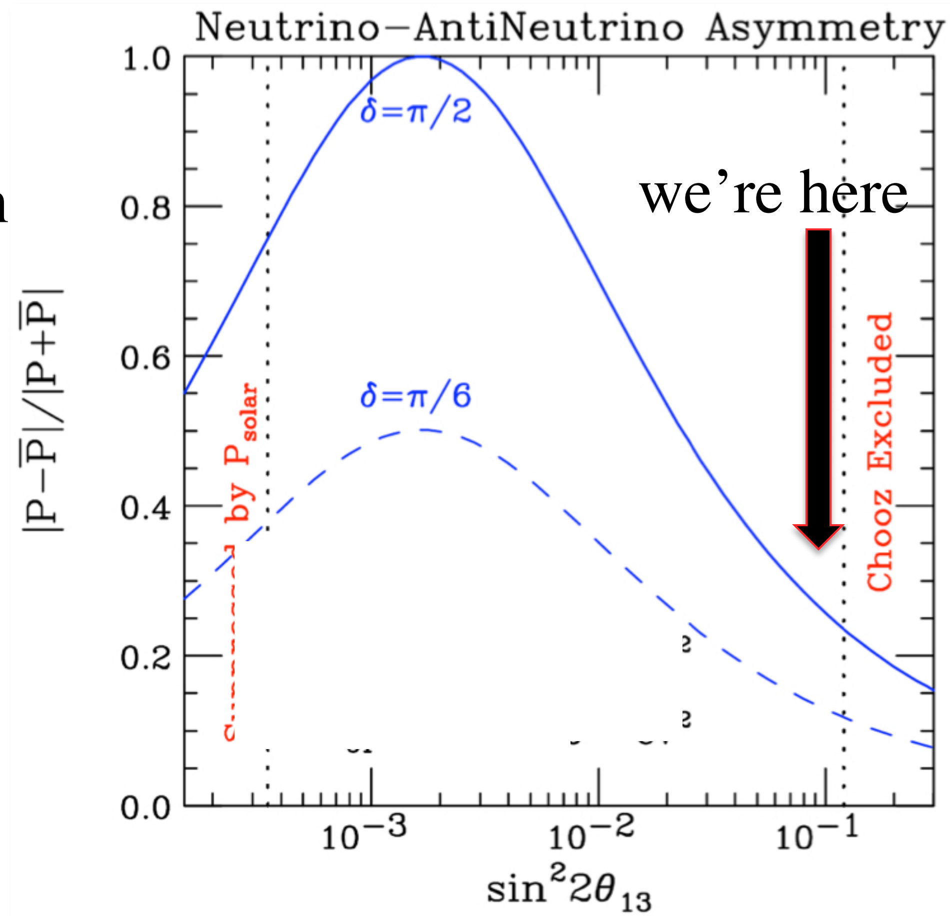
Why are ν_e Cross Sections Important?

- ν_e A – scattering results are interesting on their own.
- Recent determination of large θ_{13} has opened up possibilities of
  - Determining ν mass ordering.
  - Searching for CP-violation in the ν sector.
- To be sensitive to these effects, current/near-future long-baseline experiments will be looking for ν_μ to ν_e and $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillations over a range of energies.
- These will no longer be only "counting" experiments but rather will depend on observing distortions in the far detectors neutrino energy spectrum in **both neutrino and anti-neutrino samples.**



Why are ν_e and $\bar{\nu}_e$ Cross Sections Important?

- Large θ_{13} means we could have reasonable statistics.
- However, as the now-well-known plot at right suggests, the asymmetry between ν and $\bar{\nu}$ will be small and the goal of constraining the range of δ will demand minimal systematic errors.
- One of these systematics will be our knowledge of ν_e and $\bar{\nu}_e$ cross sections in the relevant energy range.



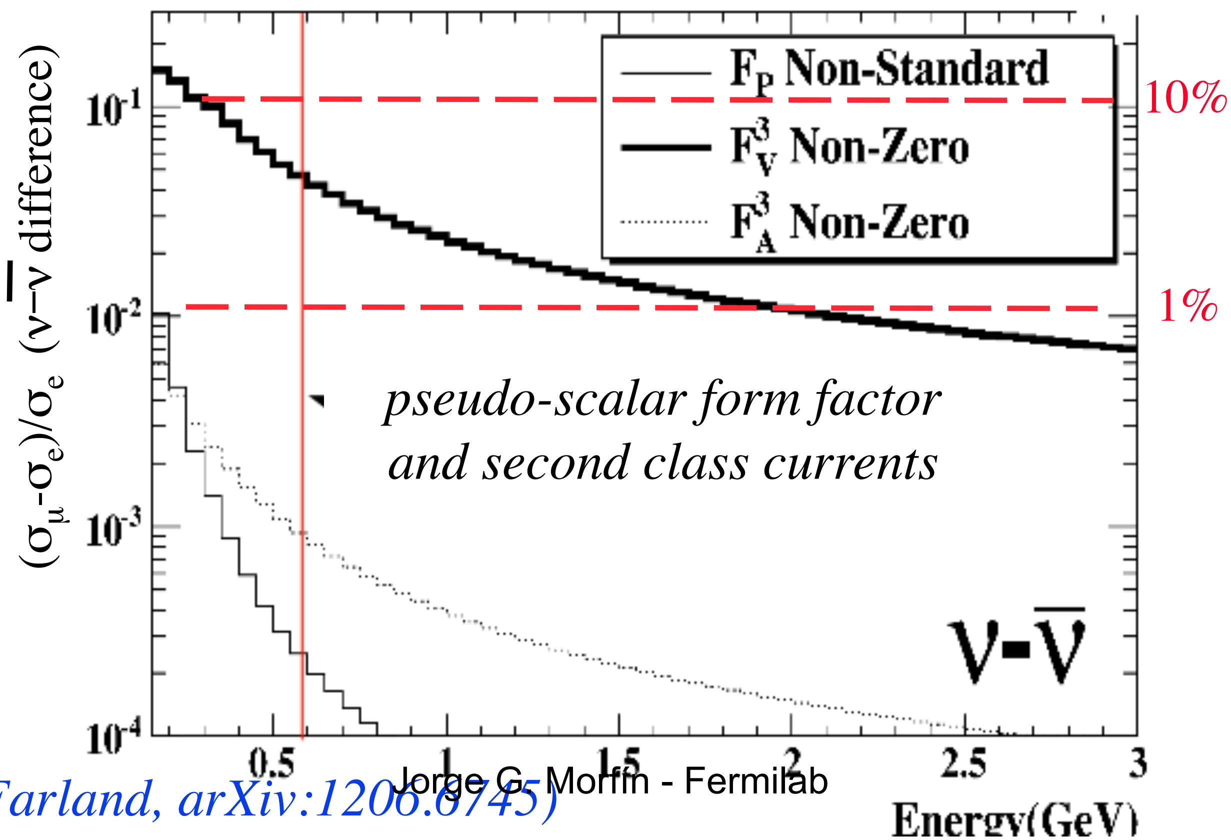
(not including matter effects & backgrounds)

(S. Parke)

What are the Differences $\sigma_{\nu\mu}(E)$ and $\sigma_{\nu e}(E)$? Quasi-elastic Scattering

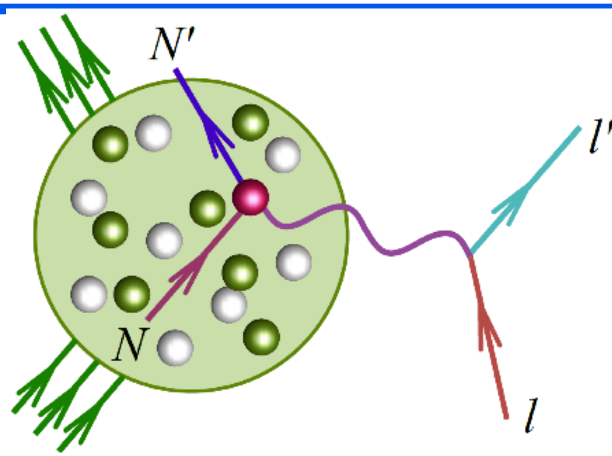
Day-McFarland study: Phys.Rev. D86 (2012) 053003

- Sources of possible differences: form factor uncertainties entering through lepton mass alterations - much more subtle:
  - Form factor contributions – both Axial and Pseudoscalar
  - Second class current contributions to vector and axial-vector form factors
- Possible contribution to CP uncertainties: effect on the FF could be different for ν and $\bar{\nu}$



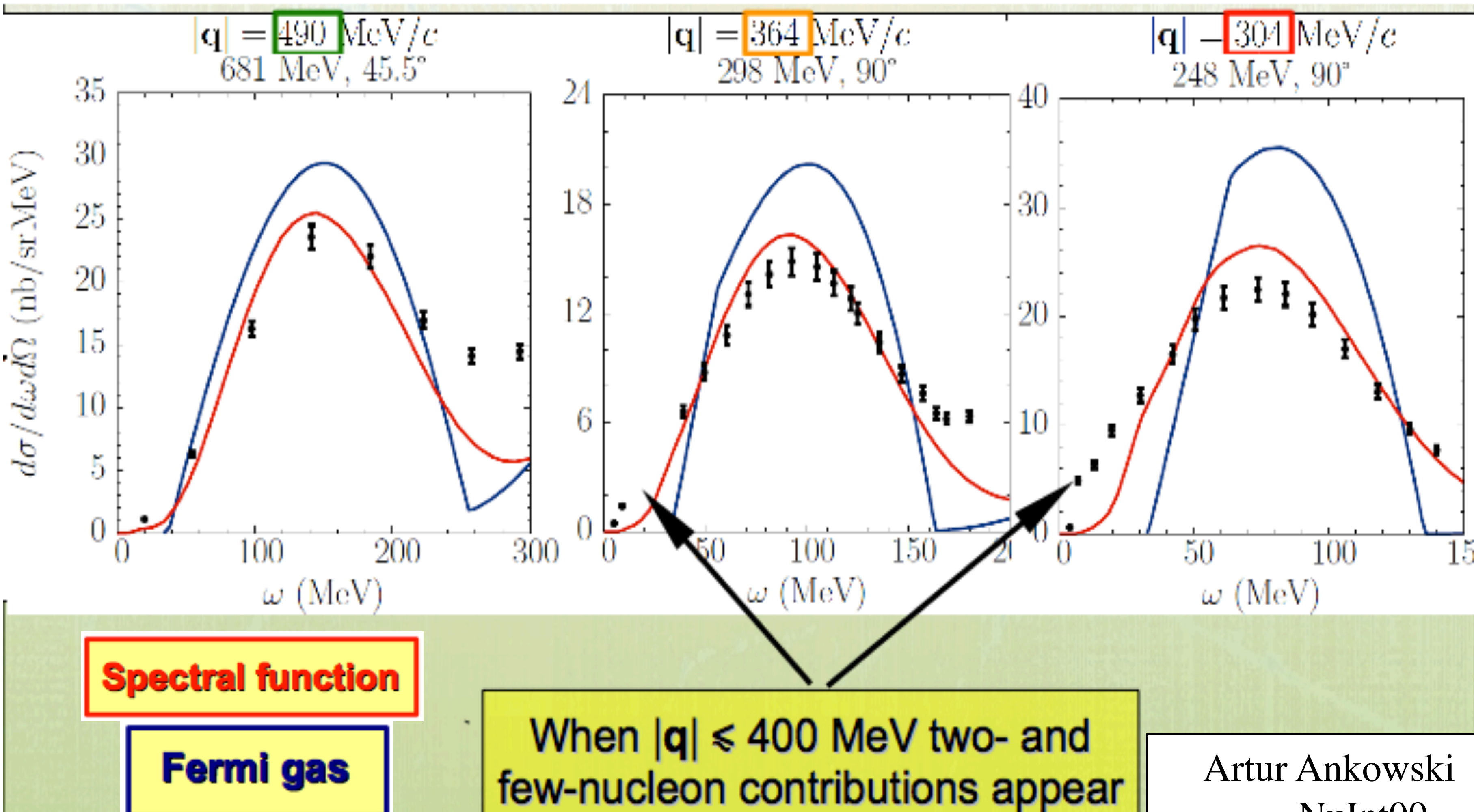
(M. Day, K. McFarland, arXiv:1206.6745)

Target Nucleon in Motion – Classical Fermi Gas Model or the Superior Spectral Functions



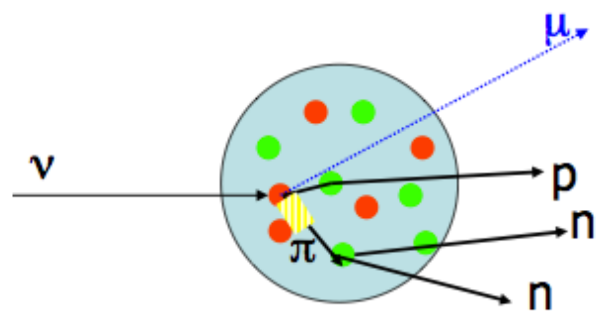
- Impulse Approximation (IA) – nucleus treated as a collection of independent nucleons – no collective excitations
  - breaks down as Q decreases with spatial resolution decreasing as 1/Q
- In the IA the nucleus is fully described by its spectral function
  - The spectral function gives the distribution of momenta and energies of the nucleons inside the nucleus
- The original model to describe this distribution is the Fermi Gas model

Spectral Function Approach Superior – Particularly as Q Decreases



Artur Ankowski
NuInt09

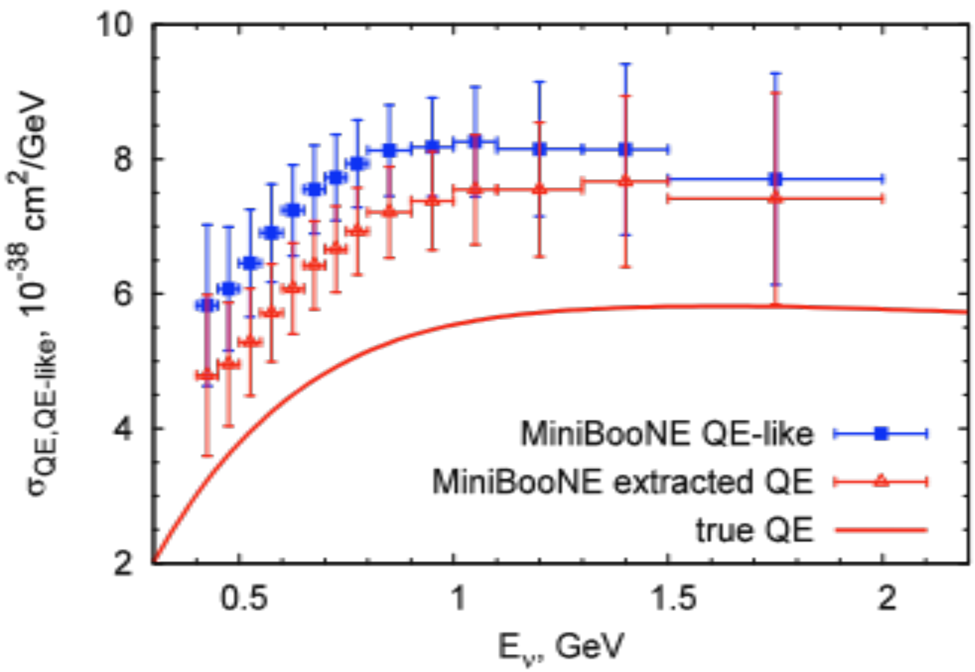
Final State Interactions (FSI)

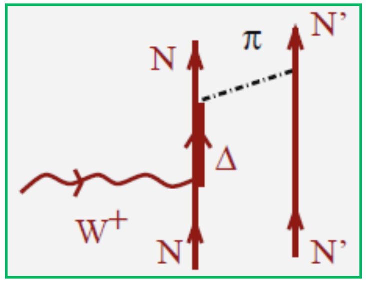


- Components of the initial hadron shower interact within the nucleus changing the apparent final state configuration and even the detected energy.
- For example, an initial pion can charge exchange or be absorbed on a pair of nucleons and an initial nucleon can scatter producing a pion

Example numbers	**Final μ p**	**Final μ p π**
Initial μ p	90%	10%
Initial μ p π	25%	75%

Attempt to Remove Resonance Background
MiniBooNE Experiment example

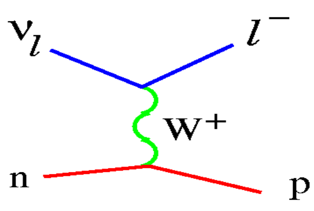




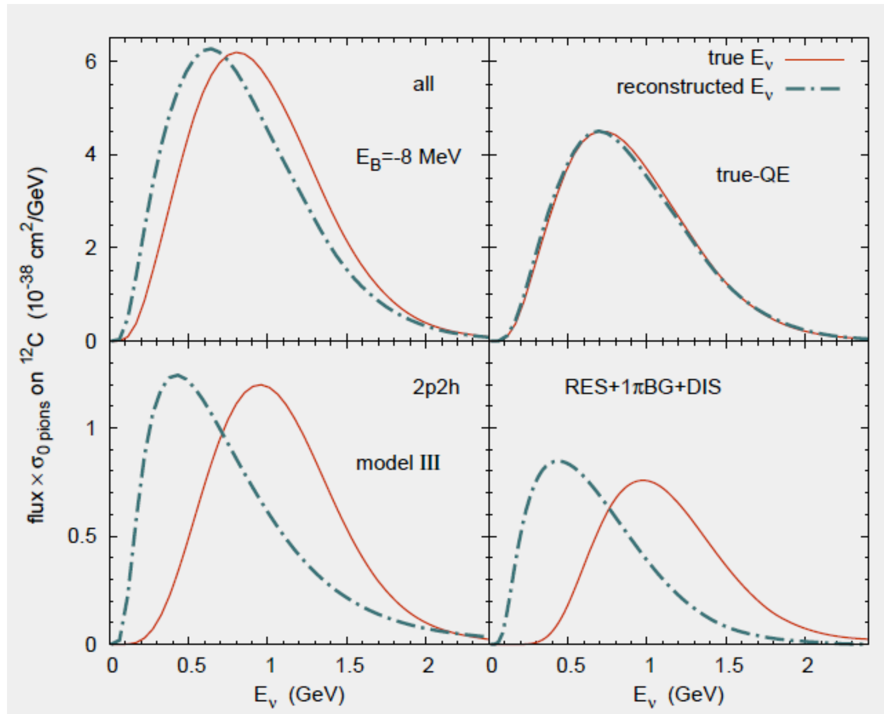
Event generator – a particular model - is used to remove QE-like background (pion absorption) from QE-like Xsect (blue) yielding an extracted QE Xsect (red)→ large pion absorption model dependence of QE result.

Nuclear Effects can Change the Energy Reconstruction for "QE" Events

- In pure QE scattering on nucleon at rest, the outgoing lepton can determine the neutrino energy:



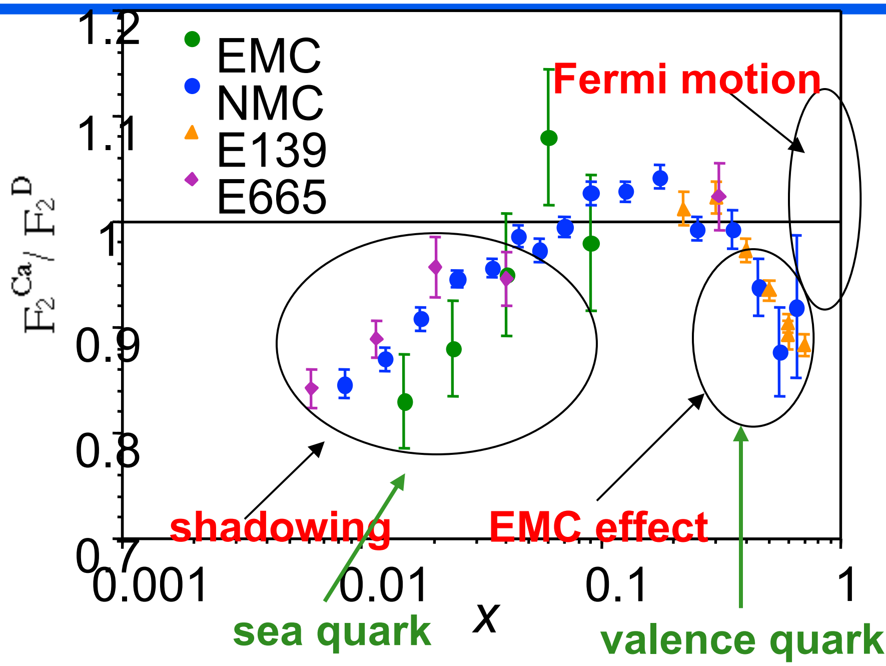
$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

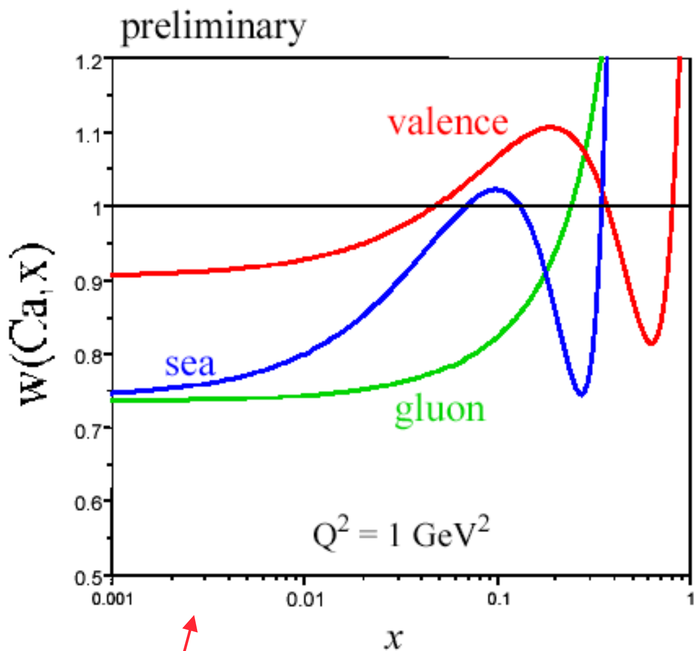


Since all modern experiments contain nuclei as targets. Reconstructed energy shifted to lower energies for all processes other than true QE

U. Mosel GiBUU

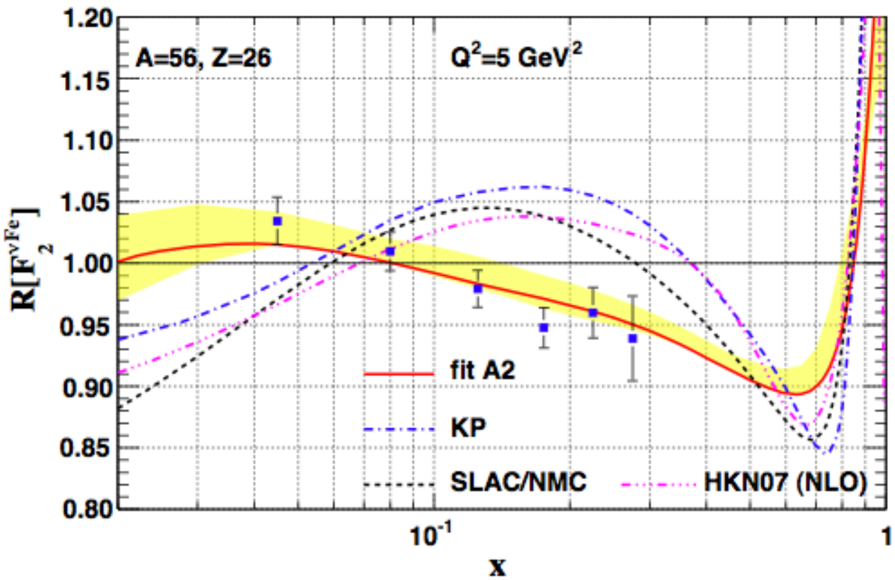
Experimental Studies of (Parton-level) Nuclear Effects with Neutrinos: until recently - essentially NON-EXISTENT





- F_2 / nucleon changes as a function of A. Specifically measured in μ/e - A **not in ν − A**
- **Good reason to consider nuclear effects are DIFFERENT in ν - A**.
  - **Presence of axial-vector current.**
  - **SPECULATION: Stronger shadowing for ν -A but somewhat weaker "EMC" effect.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**

F_2 Structure Function Ratios: ν-Iron
nCTEQ Collaboration



$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$